Demonstrated High-Performance, High-Power Skutterudite Thermoelectric Modules for Terrestrial Applications (C-32)

presented at

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Thermoelectric Systems and Devices: Device Development and Validation

Pasadena, CA USA

Terry J. Hendricks, Fivos Drymiotis, Obed Villalpando, Kevin Yu, Kevin Smith, Billy C.-Y. Li, Samad Firdosy, Jean-Pierre Fleurial, Chen-Kuo Huang, Pawan Gogna, David J. Neff

Power and Sensor Systems Section

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA

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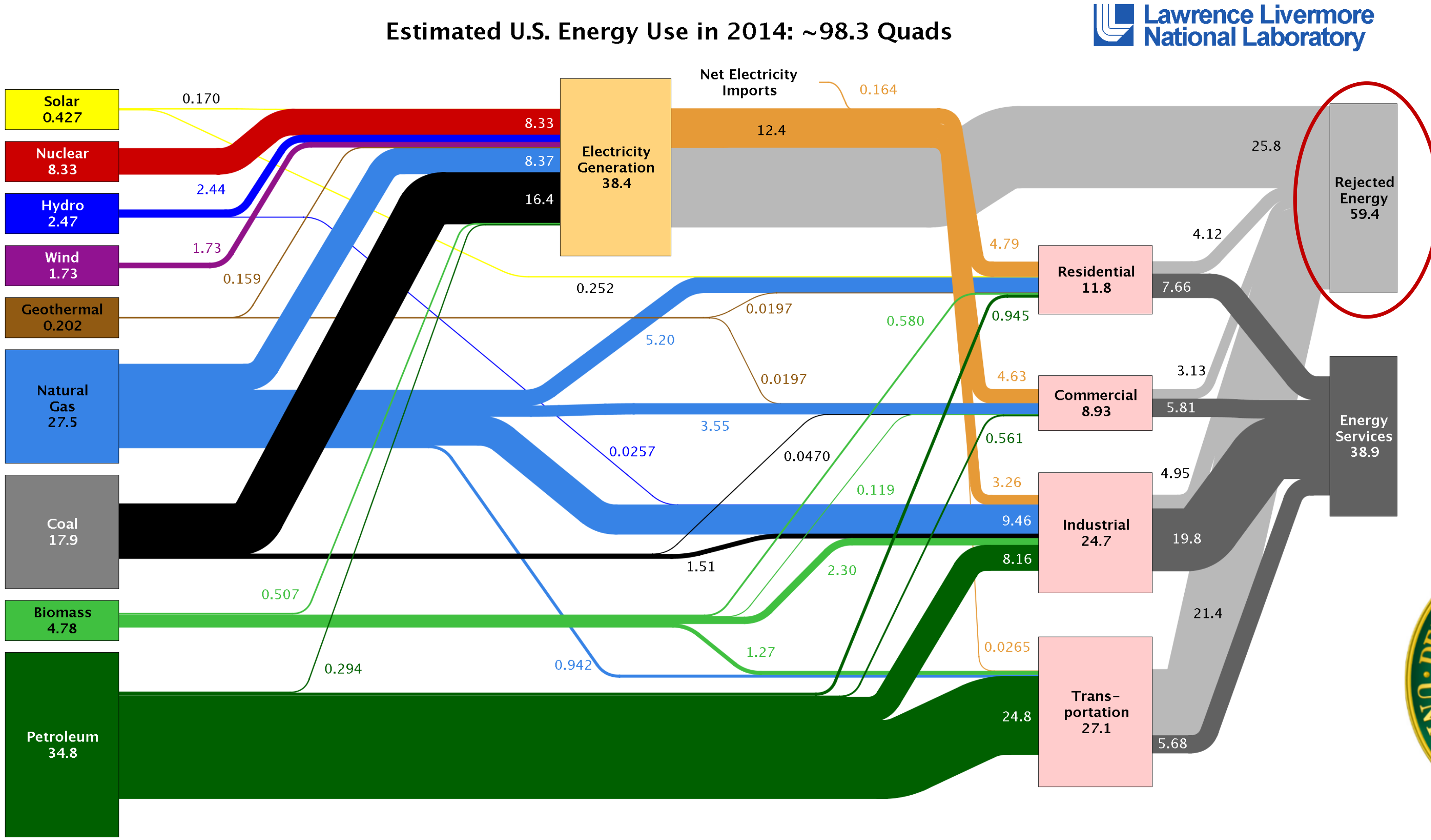
AGENDA

- Terrestrial Energy Recovery Applications
- JPL's System-Level Requirements Development
- JPL Skutterudite TE Module Development
- Skutterudite TE Module Testing Results & Analysis
- Conclusions & Next Steps

United States Energy Flow



Source: LLNL 2015. Data is based on DOE/EIA-0035(2015-03), March, 2014. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant "heat rate." The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential and commercial sectors 80% for the industrial sector, and 21% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

- Waste Heat To Be "Harvested"

  59.4 Quads

- Up ~ 5Quads From 2009

Terrestrial Industrial Process Waste Heat Recovery

- System Solutions Needed to Recover Energy Throughout the Industrial Processing Complex
  - Produce Power
  - Residential & Commercial Space Heating
  - Radiant Collectors, Rankine cycles, Stirling cycles, & Thermoelectric Conversion
  - High-Temperature TE & Structural Materials and Systems; High Temperature Thermal Energy Storage
- Steel Industry
  - Electric Arc & Blast Furnaces, Steel Slabs, Slag By-Products
  - 10's of Megawatts of Thermal Energy Available in Each Potential Location in Steel Processing
  - Process Temperatures Available: 200-1000°C
  - 13 GW Total Potential Power Production in U.S. Alone
- Various Other Industrial Processes
  - Glass Furnaces, Aluminum Processes, Petro-chemical All Have Common Requirements
  - Process Temperatures Available: 760 – 1400°C
  - Another >39 GW Potential Power Production in These Industries in U.S.
  - Large International Interest in WHR Systems
    - Latest International Conferences on Thermoelectrics 2016, Wuhan, China & 2015, Dresden, Germany
    - Energy Harvesting - 2014 U.S. Emerging Technology Conference & Exhibition, Santa Clara, CA

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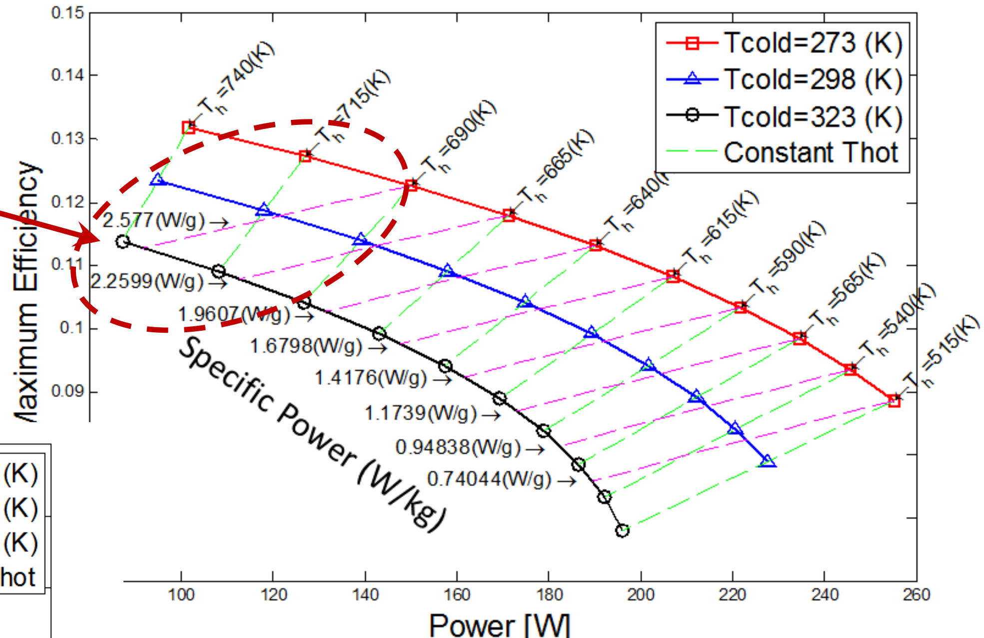
Terrestrial Waste Energy Recovery

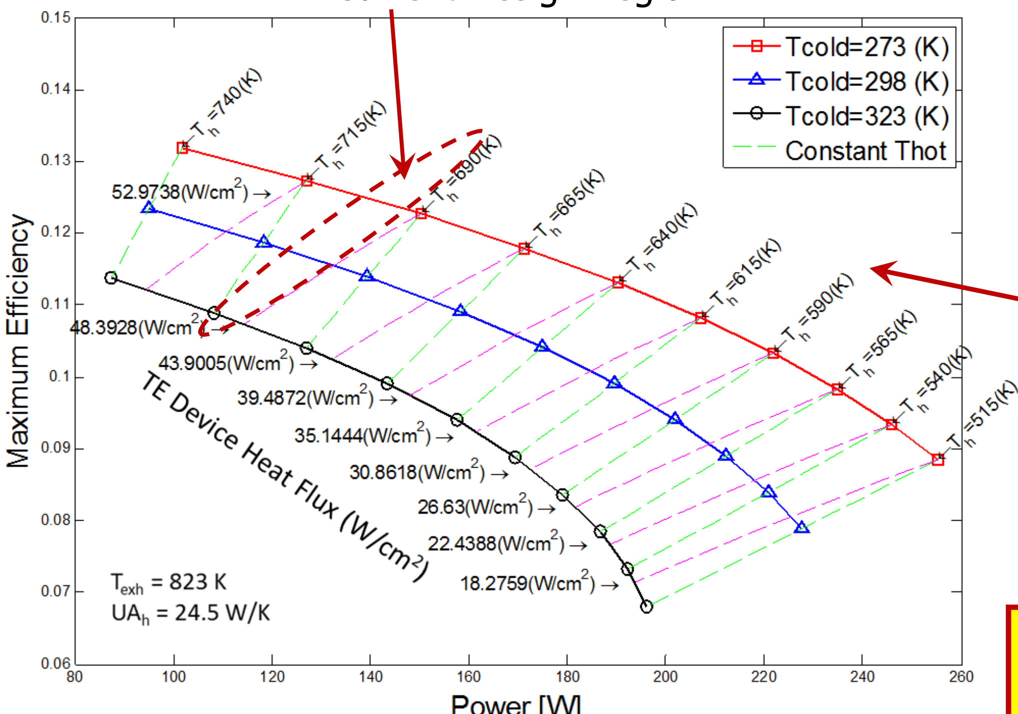
- Thermoelectric Systems Considered a Prime Energy Recovery Technology Candidate / Option in Many Terrestrial Applications
- Terrestrial Energy Recovery Goals are Often Tied to:
  - Energy Savings
  - Environmental Savings and Impacts
  - Maximizing Conversion Efficiency
  - Maximum Power Output
- However, JPL is Currently Working on System Designs Where the Critical Design Metric is Maximizing Specific Power (W/kg)
  - Knowing Its Relationship to Maximum Power or Efficiency Points is Key
  - T_{exh} = 823 K; T_{amb} = 273 K
- System Analysis Shows This Design Metric Requires High Power Flux and High Heat Flux TE Modules
- Cost-Effectiveness and Performance Are Constant Requirements

TE System Design Regime Results
T_{exh} = 823 K, T_{cold} = 273 – 323 K

- High TE Device Specific Power Regime Identified
  - Coincides with High Efficiency Regimes
  - But Coincides With Low Power Regions



Current Design Region



- Also Critical to Identify and Map the Constant TE Device Heat Flux Regions
- High TE Device Heat (and Power) Flux Regions Correspond with High Specific Power Regions
- Design Challenge Associated with High S.P.

JPL developing high performance skutterudite-based TE modules to meet these requirements

Relating System-Level Metrics to Module Metrics

- Module level and TE element level information are readily quantified and interrelated

$$P''_{TE} = q''_{TE} \cdot \eta$$

$$P''_{MODULE} = P''_{TE} \cdot F$$

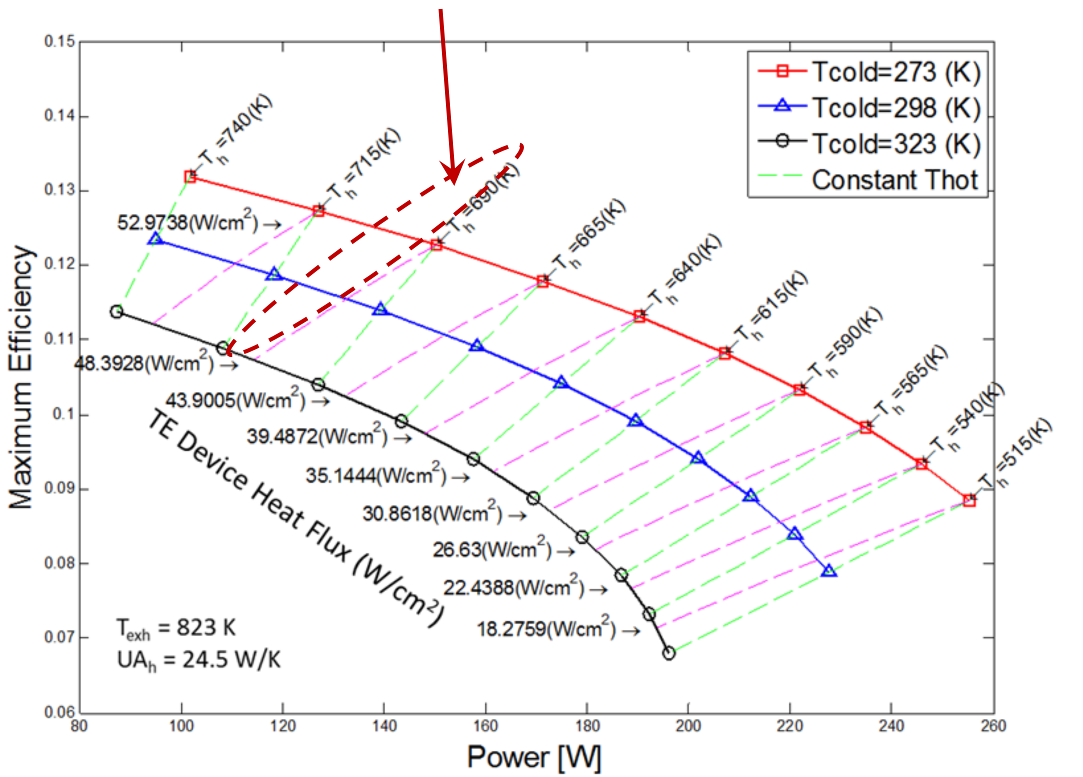
(F = Module Fill Factor; η = Module Conversion Efficiency; P'' = Power Flux)

- Heat exchanger and TE module heat fluxes also readily quantified and interrelated

$$q''_{HEX} = q''_{TE} \cdot F$$

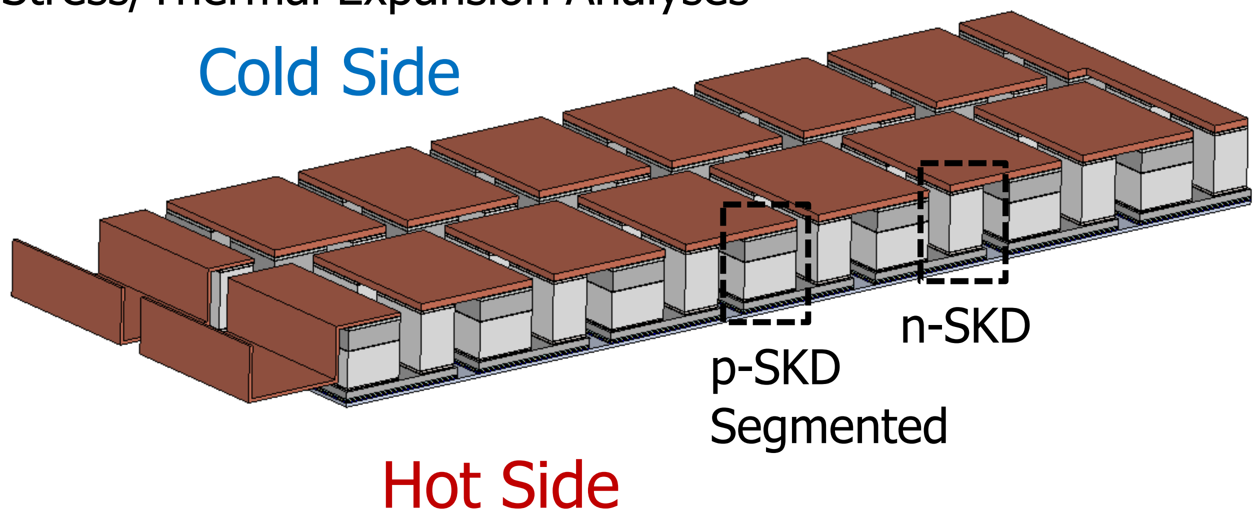
- TE module and TE element conditions are then strongly coupled to this map

Current Design Region



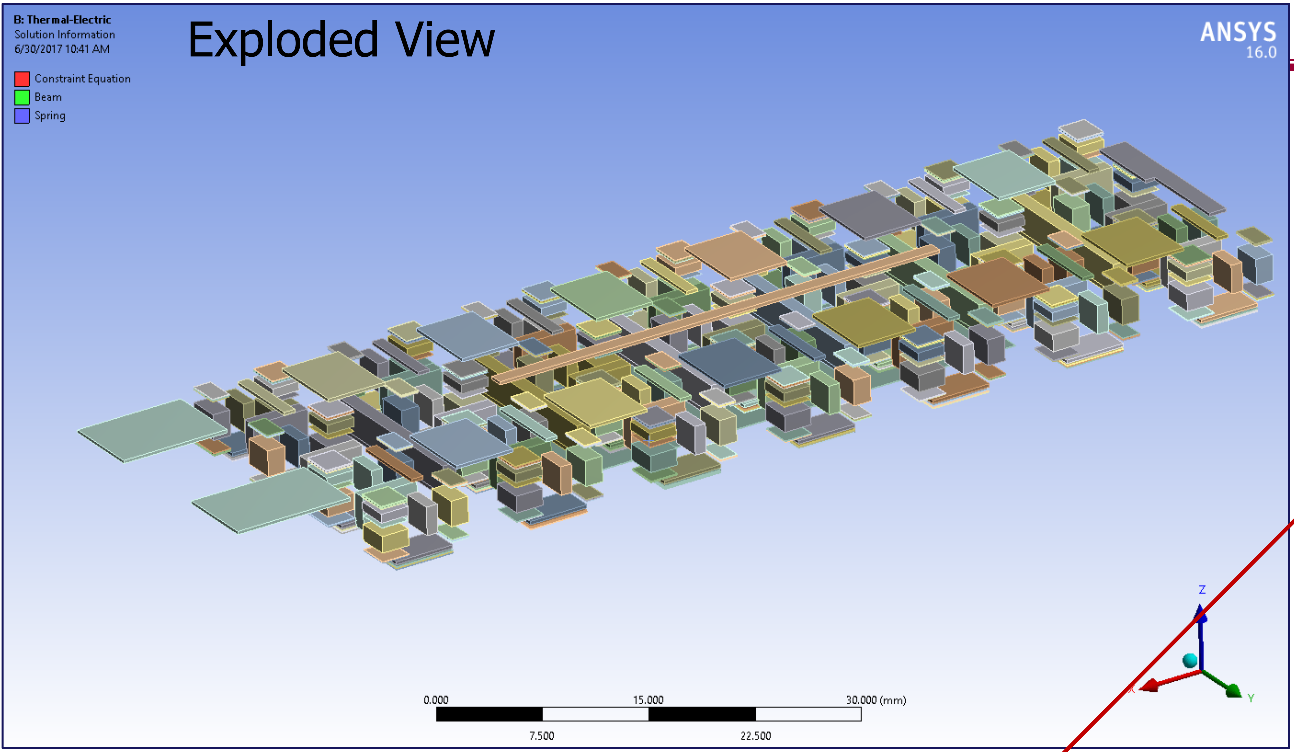
¼ Module CAD Description

- SolidWorks CAD Modeling
- SolidWorks CAD Information Transferred into Several FEA Environments
  - Electrical/Thermal/Thermoelectric Analyses
  - Structural Stress/Thermal Expansion Analyses

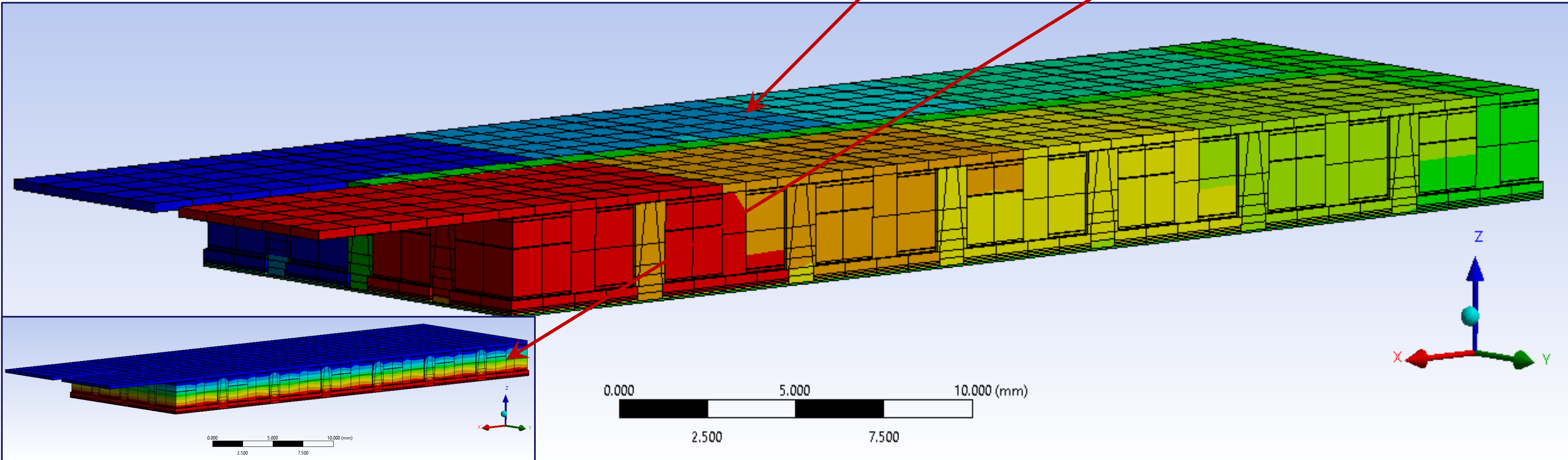


- 28 Couple Module
- Series/Parallel Connection
- Critical Interface Layers Designed In
  - Couple Electrical Isolation
  - Material Diffusion Layer
  - Bonding Metallization Layer

¼ Module FEA – High Resolution FEA Guiding Design

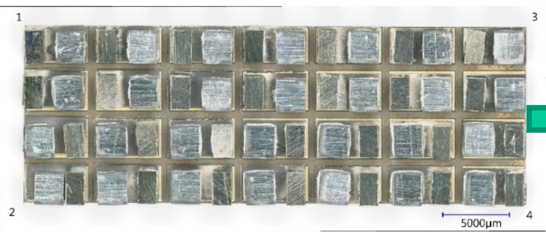


- Aerogel Incorporated in the Design.
- Bonded Contacts.
- Mesh Statistics, Nodes:27292, Elements: 46.39
- Voltage Distribution
  Red: Voc
  Blue: Ground
- Temperature Distribution
  T_{Hot} ~ 700 K
  T_{Cold} ~ 290 K

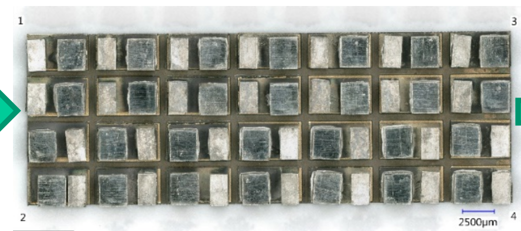


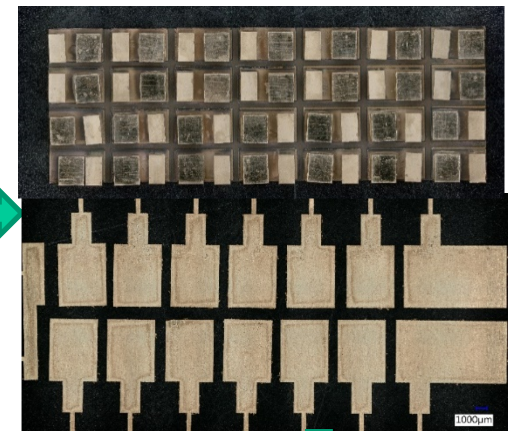
Quarter Module |Bonding Process Development (All Skutterudite Module)

Bonding of T.E. elements onto hot side



Surface etching of T.E. elements for cold side bonding

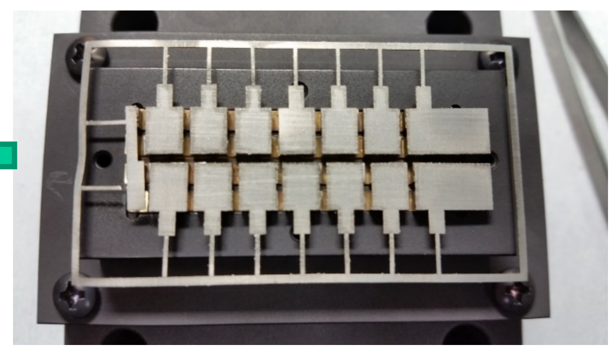




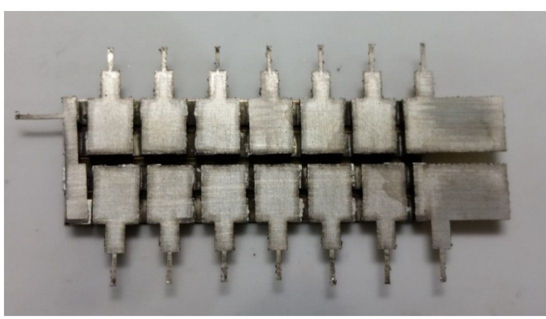
Metallic coating of module & stencil

Application of bonding paste

Cold side bonding of metal stencil



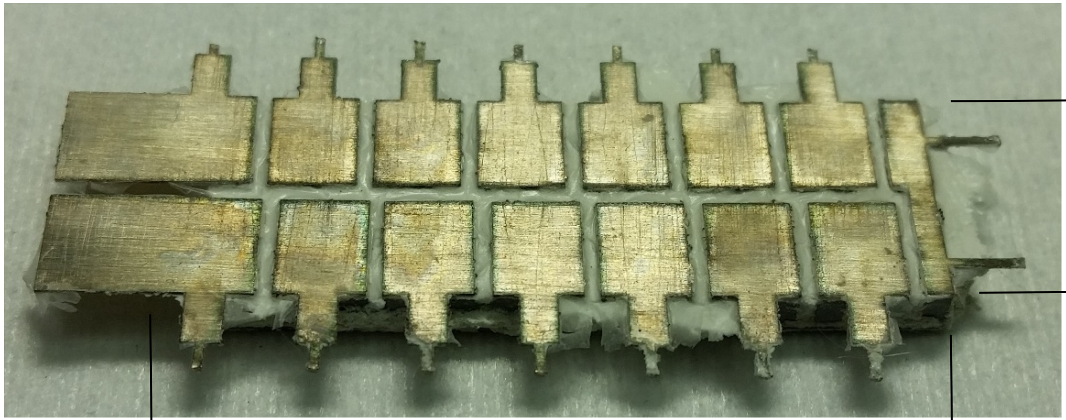
Removal of stencil frame via laser cutting



Big Success!

Module Fabrication Demonstrated & Module Completed for Testing

- Module after the aerogel process (removed excess aerogel)
- Module Aerogel process refined
- TE module generally looked very good and as expected
- Fabrication process now set for this module design
- TE module went to testing:
  - Voc
  - I-V curve
  - Thermal interfaces

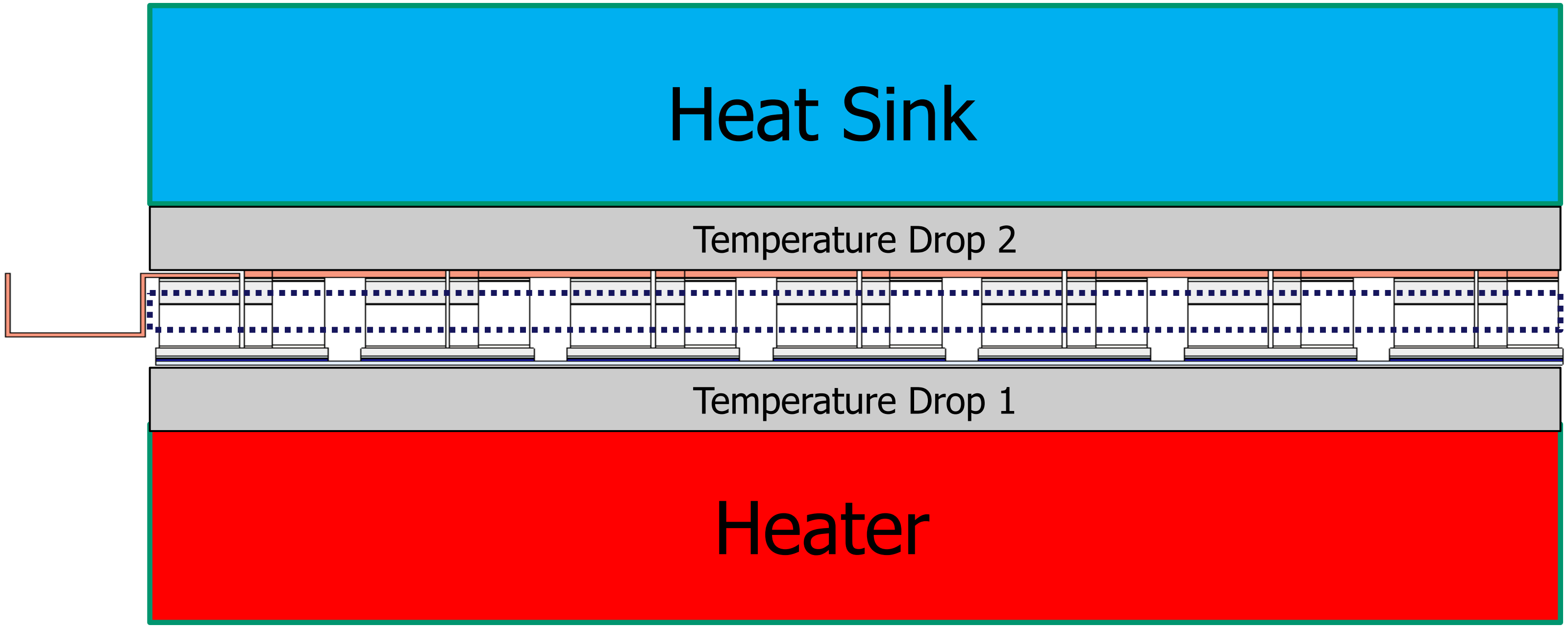


~1.35 cm

~3.9 cm

¼ TE Module Technical Challenges

- ❑ Temperature Drops Across Hot and Cold Side Interfaces.
- ❑ Average Electrical Contact Resistance Between Components.

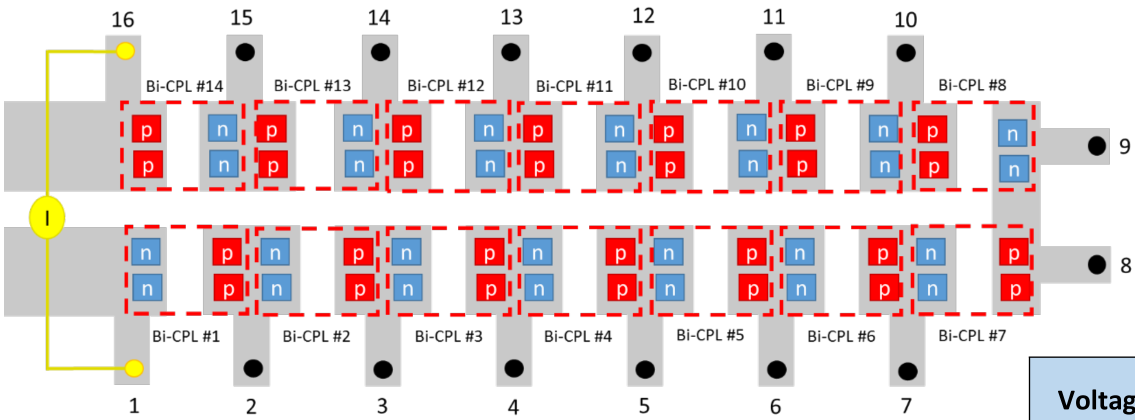


Analytic Approach

- ❑ Temperature Drops due to Interface Thermal Resistance are Estimated Based on Measured Value of Open Circuit Voltage (Voc) and Measured T_{Cold}. (Verified via testing)
- ❑ Hence, T_{Cold} is Kept Constant and T_{Hot} is varied until Calculated V_{oc} matches Measured Value.
- ❑ Average Electrical Contact Resistance Between Components is Subsequently Calculated Based on Measured I-V curve.

TE Module Testing

Resistance measurements for quarter module 6



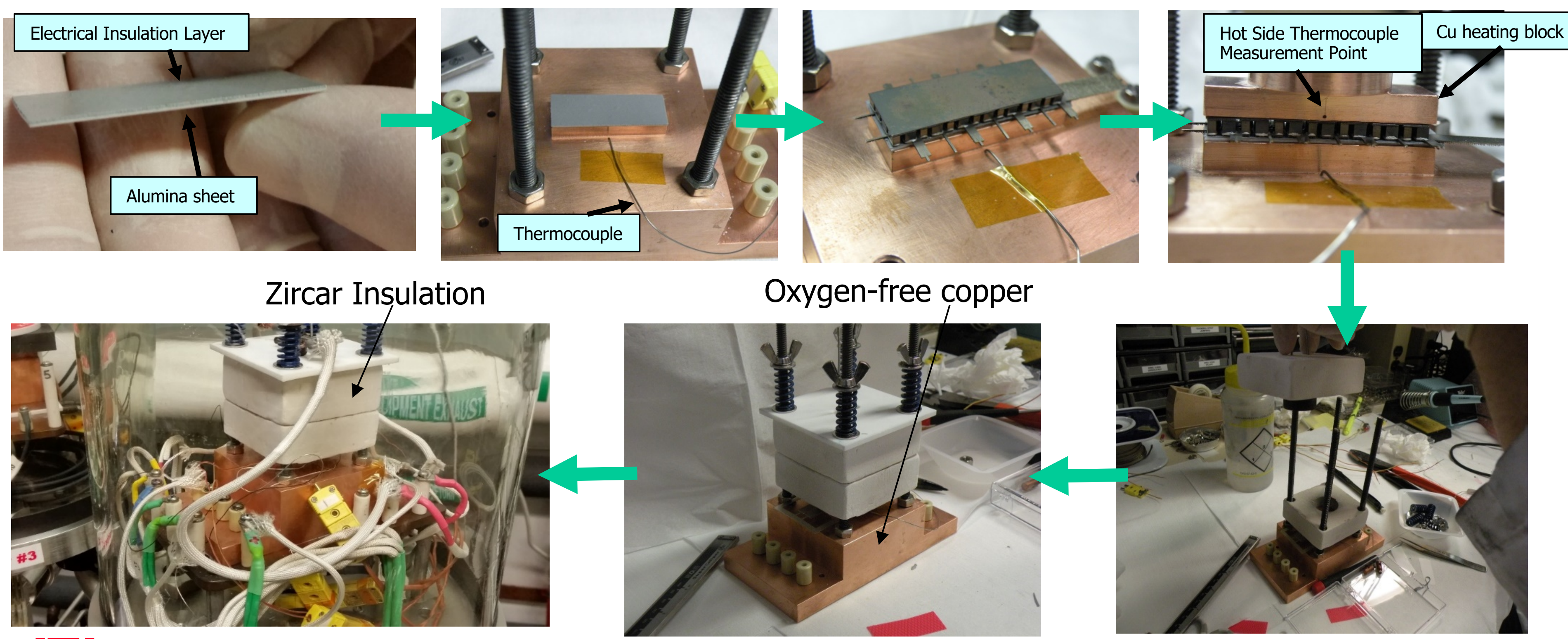
$R_{\text{Bi-CPL Calculated}}$ (mΩ):	3.14
½ $R_{\text{total device calculated}}$ (mΩ):	21.99
$R_{\text{total device calculated}}$ (mΩ):	43.98

- Current leads were attached to nodes 1 and 16 and an AC current of **0.943 A** was applied to the module
- Voltages were then measured between nodes (e.g 2→3, 3→4, 4→5, etc.)
- All resistances were in accordance with the calculated values shown at the top right
    - **Percent differences were all ≤8 % (better than Module 5)**

Voltage Probe Location Along Device	Measured Voltage AC (mV)	Measured R (mΩ) Calculated from measured V and measured I	Percent Difference (%)
$V_{1\text{-}16\ (\text{total})}$	41.65	44.17	0.43
$V_{1\text{-}9\ (\text{half})}$	19.88	21.08	4.13
$V_{9\text{-}16\ (\text{half})}$	20.67	21.92	0.32
$V_{1\text{-}2}$	3.02	3.20	1.99
$V_{2\text{-}3}$	3.11	3.30	5.03
$V_{3\text{-}4}$	2.79	2.96	5.78
$V_{4\text{-}5}$	2.81	2.98	5.10
$V_{5\text{-}6}$	2.75	2.92	7.13
$V_{6\text{-}7}$	2.76	2.93	6.79
$V_{7\text{-}8}$	2.93	3.11	1.05
$V_{9\text{-}10}$	2.84	3.01	4.09
$V_{10\text{-}11}$	2.94	3.12	0.71
$V_{11\text{-}12}$	3.15	3.34	6.38
$V_{12\text{-}13}$	2.74	2.91	7.46
$V_{13\text{-}14}$	2.95	3.13	0.37
$V_{14\text{-}15}$	3.16	3.35	6.72
$V_{15\text{-}16}$	3.07	3.26	3.68
$V_{1\text{-}16\ (\text{after all measurements})}$	41.41	43.91	0.15

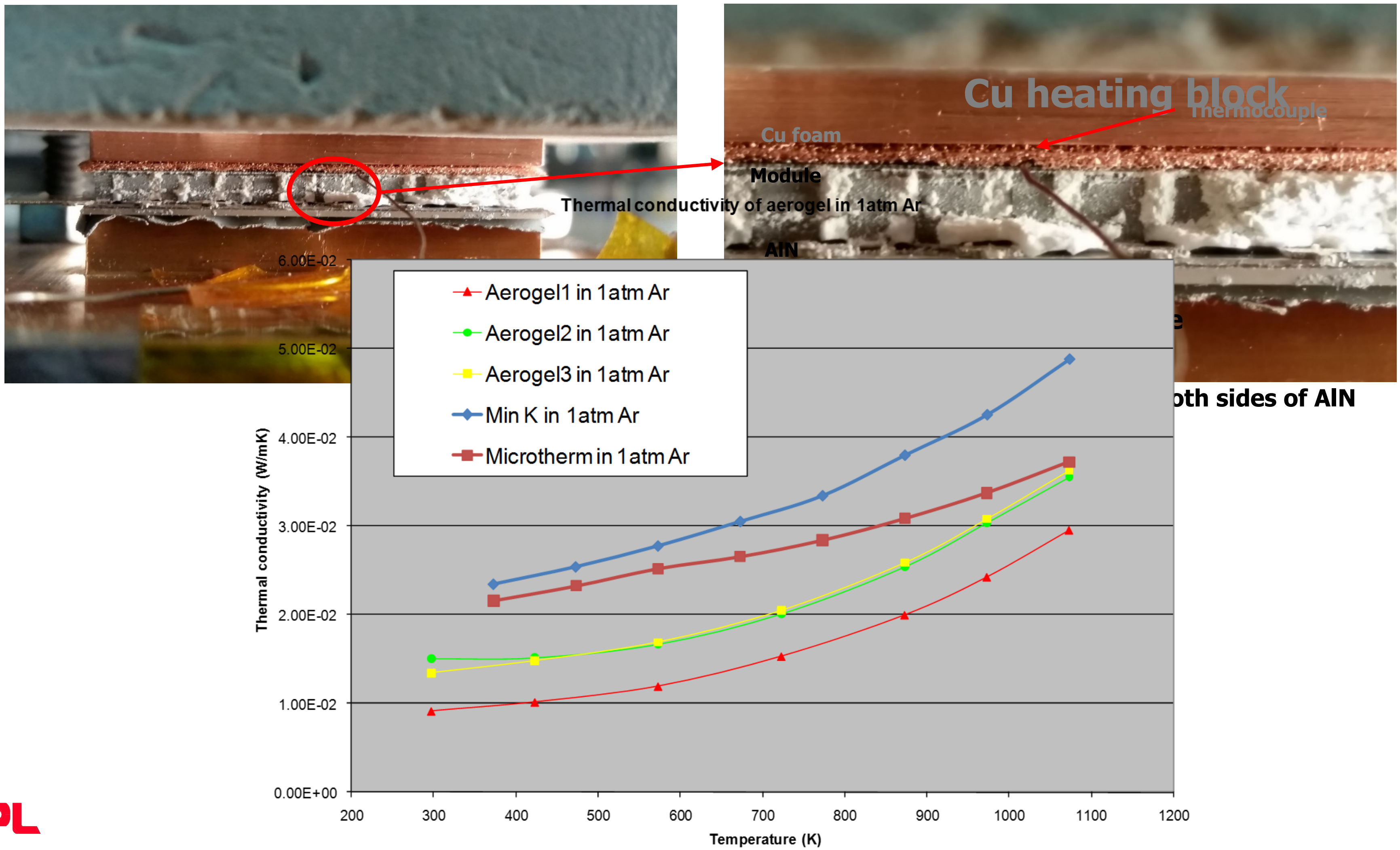
Quarter TEC Module Life Testing Loading Process

- Test system operational
- Expected measurements Hot- & Cold-Side Temperatures
  - Voltages & Currents (I-V Curve)
  - Power Output
  - Electrical Resistance
- Currently optimizing the test system and test fixture to provide consistent test results
- Similar to many other test fixtures @ JPL TEC Group



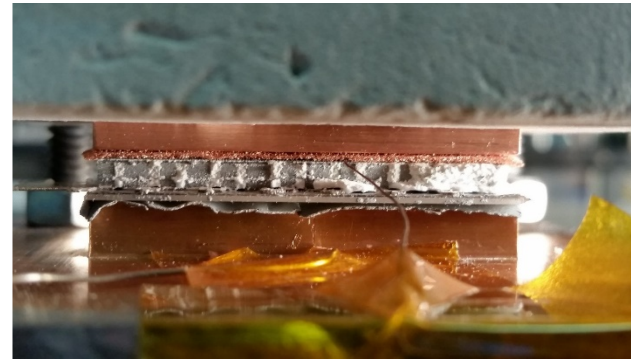
Images of module and thermocouple placement inside test fixture

- Temperature sensor locations were critical to establish internal ΔT's
- Aerogel insulation around TE elements quite apparent
- Aerogel is certainly a key design feature

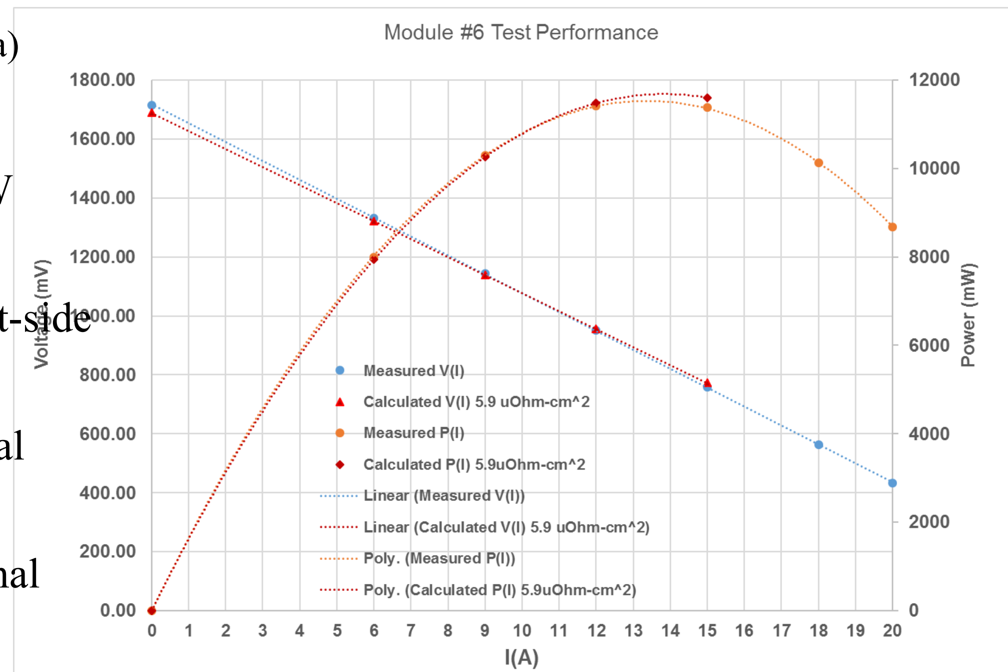


TE Module Testing

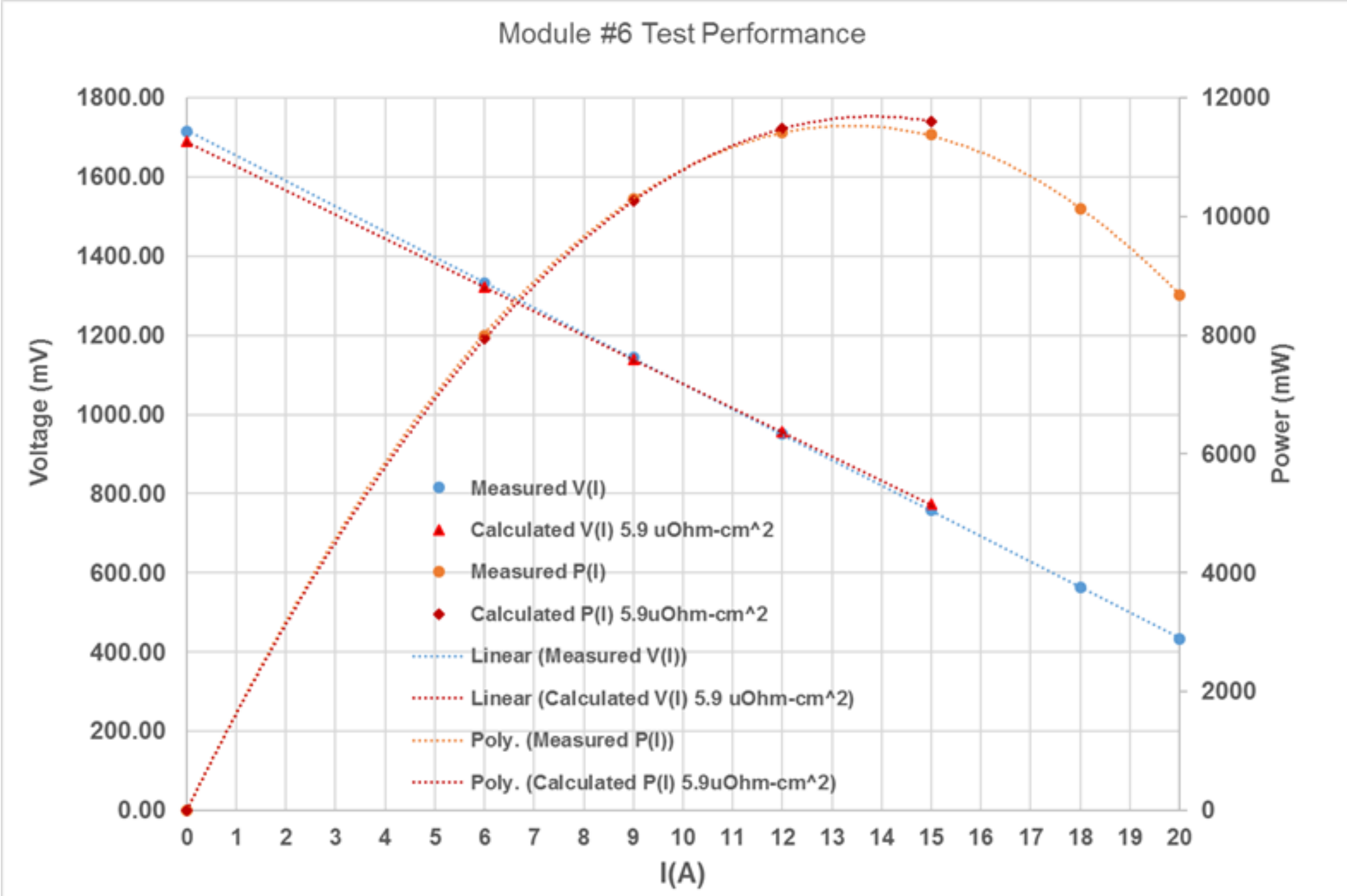
- Latest TE module test data looking better than ever
- Full I-V curve with comparison to model predicts
- Module measured resistance via I-V curve = 64.1 mΩ at temperature - Good compared to expected 60 mΩ
- Power output was 11.5 W at T_h ~425°C and T_c ~ 35°C
  - Best Ever for JPL All-SKD TE Module
  - Power flux > 2.1 W/cm^2 (Module Footprint Area)
  - Power flux ~5.1 W/cm^2 (TE Element Area)
- Hot-side thermal input is approximately 120 W
- Hot-side thermal resistances have now been analyzed with the aid of specific testing for hot-side ΔT's
- Working to get T_c lower now and lower thermal contact resistances at hot- and cold-sides.
- Even exposed to some thermal cycling – Internal Resistances stayed constant



Module Mounted in Test System



¼ Module I-V and Power Curves



- Excellent Agreement Between Experimental Data and Model Predictions
- Electrical Contact Resistance Between Components ~ 5.9 mOhm-cm^2 - This is quite reasonable

Summary & Conclusions

- High power density all-skutterudite TE modules under development and demonstration at JPL
- Module requirement driven from high specific power system-level requirement in current terrestrial application
- Requirements for TE module design driven by efficiency-power-specific power-heat flux map
- High power density all-skutterudite modules showing excellent power density
  - Power flux > 2.1 W/cm^2 (Module Footprint Area)
  - Power flux ~5.1 W/cm^2 (TE Element Area)
  - T_h ~425°C and T_c ~ 35°C
  - Highest Power – Highest Power Flux All-SKD TE Module ever at JPL
- Excellent agreement between experimental data and model predictions
- Module fabrication and testing on-going to improve performance even further
- Next Step is high power density segmented TE modules

Skutterudite TE Module Technology

- Skutterudite TE modules have been developed and demonstrated now
  - Demonstrated on U.S. DOE Waste Heat Recovery & Utilization Program - Automotive applications with $T_h \sim 500°C$
  - Now Demonstrated in High-Power-Density designs applicable to terrestrial power generation with $T_h \sim 450\text{-}500°C$
    - Industrial Processing energy recovery
    - Aircraft energy recovery
    - Oil and Gas system energy recovery
  - They are robust, high performance, capable of handling thermal cycling
  - Interface designs are being refined and optimized
- Skutterudite TE module technology also being extended to higher temperature ($T_h \sim 600°C$) spacecraft power applications
  - Potential eMMRTG spacecraft power systems to Mars, Ocean Worlds, Icy Moons, and outer regions of our solar system (Saturn, Uranus, Neptune, and beyond)
  - Interface designs are being refined and optimized

Skutterudite TE modules are here
They are now being refined for different applications

ACKNOWLEDGMENTS

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